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# Vulnerability of Maritime Infrastructure: A Network Science Approach

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## Abstract

In the last half-century, global merchandise trade has grown from a fifth of global GDP to a half, largely due to the advent of the shipping container and this, despite the recent financial crisis, is likely to grow further in its economic significance. This paper aims to analyse the vulnerability of global shipping network and the impact of hazards such as bunker fuel price rises and under-utilisation. A model of the maritime network is built using the commercial schedule of a major shipping company. This uses a network science approach where each port is represented as a node and an edge represents service between the connecting ports. Edges weights are derived using an improved model of the transport costs. Different centrality measures and their distribution form the basis of performance assessment of the network and the ports. It is observed that (a) the global operations depend on the continued availability of a small percentage of the ports and (b) the changes in bunker fuel prices and utilisation on the network result in different global port hierarchies. These findings have potential uses in improving the network resilience and financial risk management. Finally, several port improvement scenarios are examined and their priority determined based on global operations.

## Key Words

Shipping network, maritime infrastructure, vulnerability and resilience, risk management.

## Introduction

The 2007-2008 financial crisis resulted in a perfect storm of economic issues for global shipping, with overcapacity, low freight demand, and rising debts plaguing the industry for nearly a decade. Across the industry, utilisation fell to approximately 75% and losses were made in the subsequent years resulting “in a race for market share”<sup>1</sup>. This culminated in the bankruptcy of Hanjin Shipping, once “South Korea's biggest shipper and number seven in the world”<sup>2</sup>. Despite the evident overcapacity in the global network, Maersk has continued to develop ever larger ships up to 18,000 TEU (Twenty-foot Equivalent Unit)<sup>3</sup>. This trend has accelerated since the announcement of the Panama Canal expansion project, completed in 2016.

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<sup>1</sup> Glave, T., Joerss, M. & Saxon, S. The hidden opportunity in container shipping. McKinsey & Company (2014).

<sup>2</sup> Illmer, A. Hanjin: Final curtain falls on shipping saga. BBC News.

<sup>3</sup> Kremer, W. How much bigger can container ships get? BBC News.

Considering the problems facing the industry, the aim of this paper is to examine the global shipping network and its vulnerability to a range of hazards. After a brief review of the literature in the next section, a model of the global shipping network is built. This is based on a network science approach and uses the local schedules of a major liner to create a global model of the network. In the following sections, the model is used to examine the vulnerability of the global network and to study the effects of overcapacity and rising fuel costs. The penultimate section examines several port improvement scenarios. The final section summarises the key findings and limitations.

## Literature review

“Vulnerability is susceptibility to damage – especially where small damage leads to disproportionate consequences”<sup>4</sup>. It derives from the internal structure of the system and may remain hidden until exposed to an external action. Vulnerability is sufficient for a lack of robustness and resilience requires robustness. Spatially distributed systems such as ports can be modelled using graphs and a range of metrics are available to examine their structure<sup>5</sup>.

Across several papers, Ducruet et al. introduced some of the first extensive applications of network theory to the maritime industry. The 2010 paper<sup>6</sup> provided an empirical model of traffic flows, upon which conventional graph theory techniques were applied. A modified betweenness centrality measure, weighted against traffic data, showed changes in the prominence of ports located on the East China Sea. González et al.<sup>7</sup> later adapted and applied these newly introduced methods globally. Cullinane and Wang<sup>8</sup> identified the weaknesses of the popular hierarchical system, whereby ports are classified as hubs, load centres, direct call ports, or feeder ports. They stress that a qualitative checklist-like approach lacks “a clear-cut definitive indicator of what actually constitutes” each category, whilst failing to consider the overall spatial characteristics of the network. They instead proposed a multiple linkage analysis, adopting centrality measures to ascertain port performance. However, a significant weakness in the methodology is that all linkages are given equal weighting.

Merk et al.<sup>9</sup> assessed the financial impact of larger vessel sizes and recognised the increase in network vulnerability resulting from service and cargo concentration. More stringent public policy and a cessation to further increases in container ship size was recommended. The rise of bunker fuel price and its global variation is considered in detail in Notteboom and Vernimmen<sup>10</sup>. Fuel consumption is considered against vessel design speed and it is recommended that schedules are reconfigured to allow for slower journeys. Furuichi and Otsuka<sup>11</sup> provide a comprehensive cost breakdown and a method of estimating canal fees at different ship sizes and utilisations. However, the study makes several blanket assumptions, for example,

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<sup>4</sup> Blockley, D., Godfrey, P. & Agarwal, J. Infrastructure resilience for high-impact low-chance risks. *Proceedings of the Institution of Civil Engineers*, 165(Civil Engineering Special Issue), (2012).

<sup>5</sup> Newman, M.E.J. *Networks: an introduction*. (Oxford University Press, 2010).

<sup>6</sup> Ducruet, C., Lee, S. & Ng, A. Centrality and vulnerability in liner shipping networks: revisiting the Northeast Asian port hierarchy. *Maritime Policy & Management*, 37, (2010).

<sup>7</sup> González Laxe, F., Jesus Freire Seoane, M. & Pais Montes, C. Maritime degree, centrality and vulnerability: port hierarchies and emerging areas in containerized transport (2008–2010). *Journal of Transport Geography*, 24, (2012).

<sup>8</sup> Cullinane, K. & Wang, Y. The hierarchical configuration of the container port industry: an application of multiple linkage analysis. *Maritime Policy & Management*, 39, (2012).

<sup>9</sup> Merk, O., Busquet, B. & Aronietis, R. *The Impact of Mega-Ships - Case-Specific Policy Analysis*. (OECD, 2015).

<sup>10</sup> Notteboom, T. & Vernimmen, B. The effect of high fuel costs on liner service configuration in container shipping. *Journal of Transport Geography*, 17 (2008).

<sup>11</sup> Furuichi, M. & Otsuka, N. Cost Analysis of the Northern Sea Route (NSR) and the Conventional Route Shipping. In: *IAME 2013 Marseille*. Chios: International Association of Maritime Economists (2013).

loading and unloading handling costs are always taken as 100 USD/TEU globally. In addition, only one connection is considered in isolation, making no allowance for the effects on global network behaviour.

In this paper, we combine the network theory based approaches, usually published in academic journals, with the cost and feasibility focused studies which tend to be published by intergovernmental organisations and industry forums. This allows us to recognise both economic factors and network topography in our analysis.

## Modelling of shipping network

We model the shipping operations using a directed network where each port is represented as a node and an edge represents service between the connecting ports. Edges connect all pairs of ports that share a route in common, regardless of whether those ports are adjacent in the schedule. Transit through a node represents the transfer of a container from one ship to another, rather than a container merely sitting idle at a port of call. Each edge has an associated weight which is derived using an improved model of the costs (explained below). We considered the established routes (well over 100) of a major shipping liner to create a representative model of the shipping network. Data on each route was obtained from the advertised schedules and public sources. For each route an adjacency matrix of monetary costs ( $C_{o,d}$ ), as illustrated in Figure 1, was created.

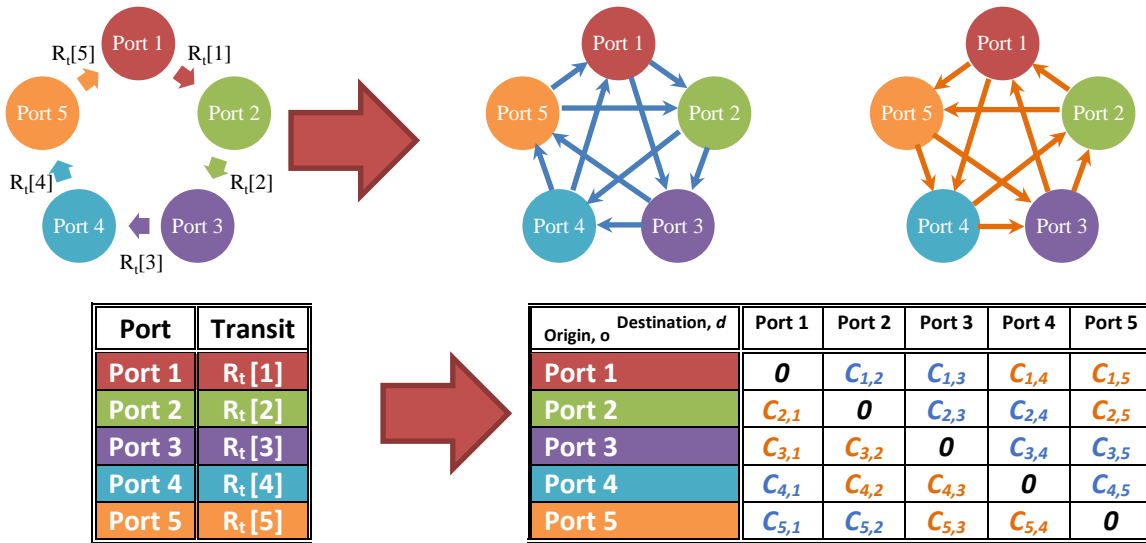


Figure 1: Generalised Schedule and the corresponding Adjacency Matrix

Figure 2 shows a breakdown of costs associated with the transportation of a shipping container. These include route costs (covering fuel, capital and running overheads), various dues at ports/canals, handling charges for loading/unloading, various surcharges etc. Details of how these costs were determined are provided elsewhere<sup>12</sup>. Many of these do depend upon the nominal vessel capacity for a given route. This in turn is dependent on the infrastructure availability (e.g. canal depth) and the utilisation (since a more laden vessel will sit deeper in the water). The *World Port Index*<sup>13</sup> was used to establish the limiting drafts at mid-tide. This considered the controlling depth of the principal or deepest channel, the greatest depth alongside the cargo pier, and the mean tidal range to the nearest metre. For routes traversing canals,

<sup>12</sup> Papaioannou, C. J. Market trends impacting Maersk's container shipping fleet: a network science approach. Undergraduate Research Report 1617RP046. Department of Civil Engineering, University of Bristol, Bristol, U.K (2017).

<sup>13</sup> World Port Index, Pub 150, National Geospatial Intelligence Agency (2016).

maximum draft values of 20.10 m, 15.20 m, 12.04 m, and 7.92 m were adopted for the Suez Canal, Panama Canal (post-expansion), Panama Canal (pre-expansion), and Saint Lawrence Seaway respectively. Optional value-added services (e.g. controlled atmosphere, garments on hangers) are all excluded from the study.

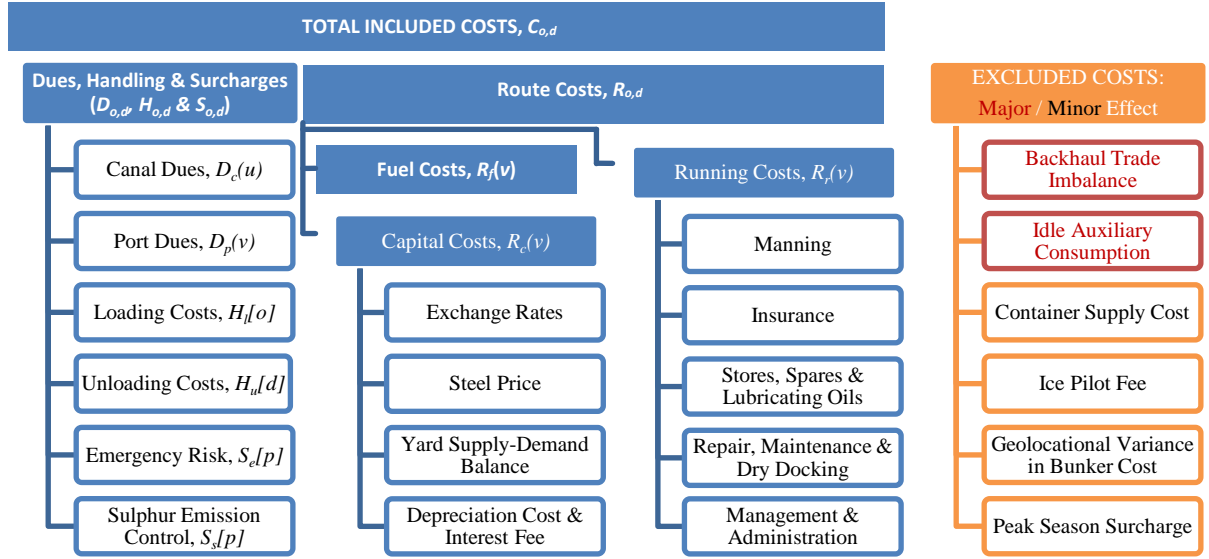


Figure 2: Schematic of shipping costs<sup>14 15 16</sup>

A global adjacency matrix was constructed by combining the local adjacency matrices. In doing so, minimum edge values  $C_{o,d}$  were used in the global adjacency matrix. A simplified representation of this process, considering three short routes only, is illustrated in Figure 3. The edge weight is proportional to the inverse square of  $C_{o,d}$ , thus allowing the variability in costs to be understood easily.

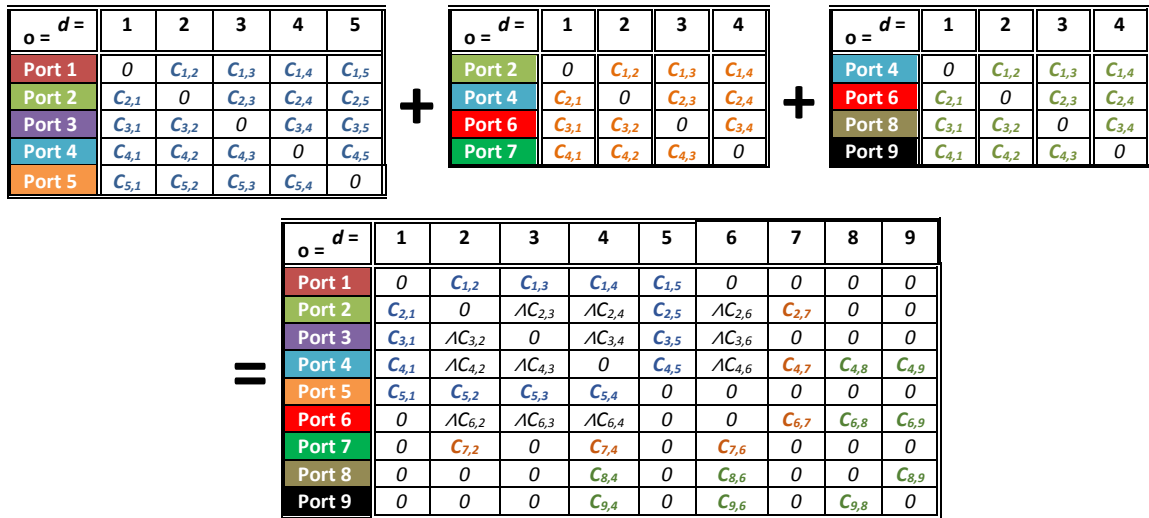


Figure 3: Combination of three local adjacency matrices to form a global matrix

<sup>14</sup>Merk, O., Busquet, B. & Aronietis, R. The Impact of Mega-Ships - Case-Specific Policy Analysis. (OECD, 2015).

<sup>15</sup> Furuichi, M. & Otsuka, N. Cost Analysis of the Northern Sea Route (NSR) and the Conventional Route Shipping. In: IAME 2013 Marseille. Chios: International Association of Maritime Economists (2013).

<sup>16</sup> Freight shipping rates and container costs. Maersk Line.

## Local network analyses

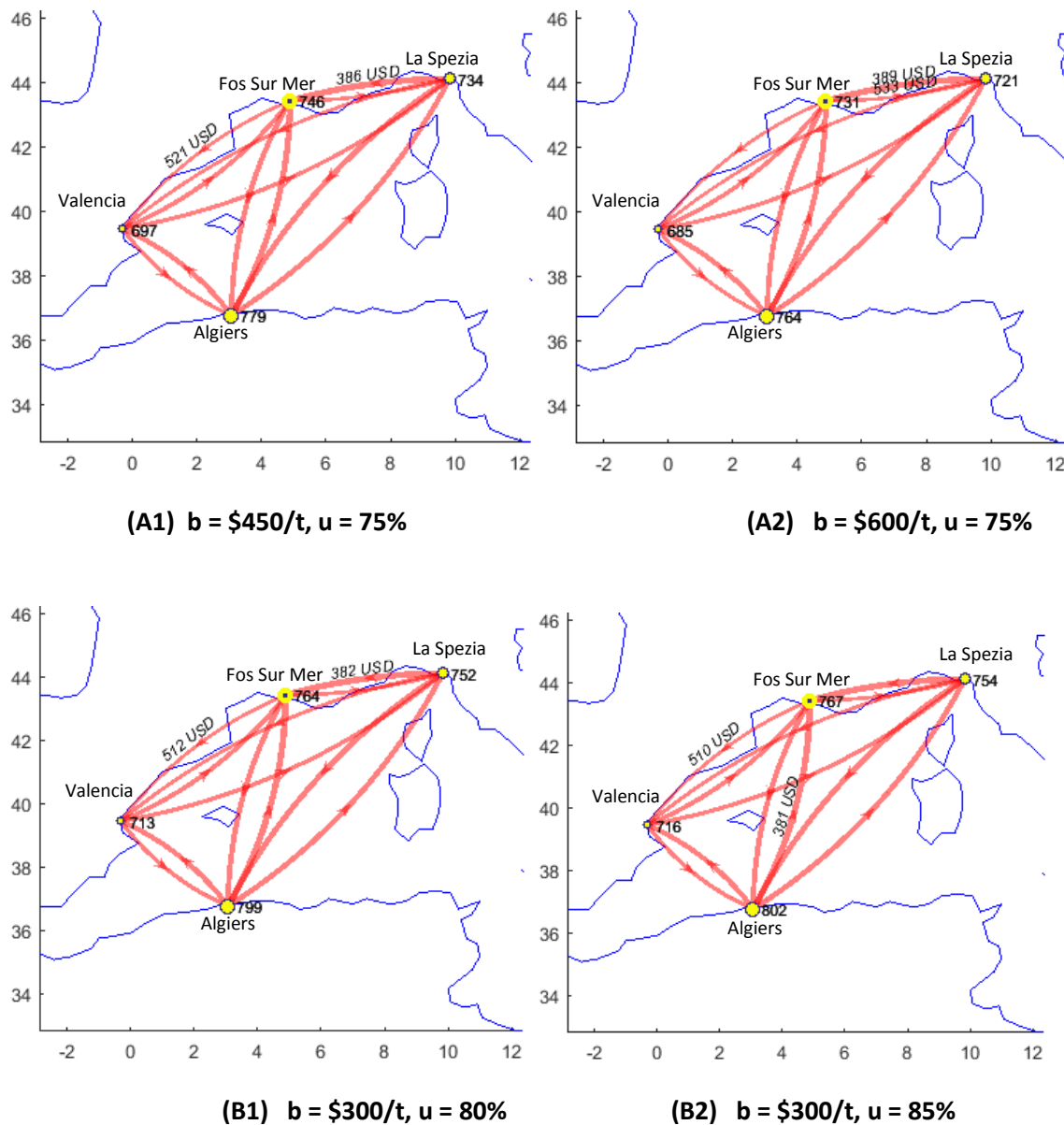
The behaviour of the all local routes considered in the construction of the above model can be broadly categorised into two groups - balanced routes and imbalanced routes. Whilst properties can vary, the following trends were observed:

### Balanced Routes

- Number of ports  $n$  is low (typically  $2 \leq n \leq 9$ )
- Low inter-port distance variability (200 ~ 900 nm)
- Similar hinterland economic development
- Loop shape
- Unlikely in areas with local cabotage laws

### Imbalanced Routes

- Number of ports is higher (typically  $6 \leq n \leq 21$ )
- Variable inter-port distance (30 ~ 5000 nm)
- Dissimilar hinterland economic development
- Loop or figure-of-eight shape if  $n$  is medium
- Figure-of-eight or linear shape if  $n$  is high



**Figure 4: Effect of fuel prices and utilisation on local routes in Algiers Sea** ( $b$ : bunker fuel price,  $u$ : utilisation. Numbers on axes represent geographical location. The size of the yellow circle indicates incloseness centrality ranks, the size of the blue disk indicates outcloseness centrality rank, whilst a turquoise circle represents equal centrality ranks. Nodal values are mean of two centralities. The maximum and minimum  $C_{o,d}$  values are displayed along the edges)

Balanced routes tend to have many journeys with similar associated costs, therefore they are highly sensitive to small changes in bunker cost or utilisation, since fluctuations can alter the cheapest way of traversing the loop. A good example of a highly-balanced route is Seago Line's Algiers Sea service (corresponding network shown in Figure 4). This service claims to specialise in intermodal transportation options, joining Fos Sur Mer, well connected to France's extensive freight rail system, with La Spezia, Valencia, and Algiers. This claim is backed up by analysis. This is assessed using incloseness centrality and outcloseness centrality, which correspond to the inverse sums of all minimum edge costs from and to all other nodes respectively. The mean of incloseness and outcloseness centrality in TEU / mn USD expresses the number of TEU that can be transferred to or from the port in question at a given cost. Figure 4(A) shows the change in response of the Algiers Sea service due to rising bunker prices. Fos Sur Mer's performance reduces from 746 to 731 TEU / mn USD, whilst La Spezia replaces Valencia as the most expensive backhaul destination port. Figure 4(B) shows the change in response of the Algiers Sea service due to fluctuations in utilisation; a 5% increase in utilisation results in Fos Sur Mer's performance increasing from 764 to 767 TEU / mn USD, whilst Algiers replaces La Spezia as the cheapest front-haul origin port.

Conversely, Maersk Line's SL Cumbia service (corresponding network shown in Figure 5) is a good example of a highly-imbalanced route, where higher handling costs and more stringent environmental regulations at US ports vastly skew the model in favour of their cheaper Central American counterparts. These routes are highly resilient against cheapest traverse switching, as demonstrated in Figure 5, where a doubling of utilisation capacity has no effect on the cheapest and most expensive journey.

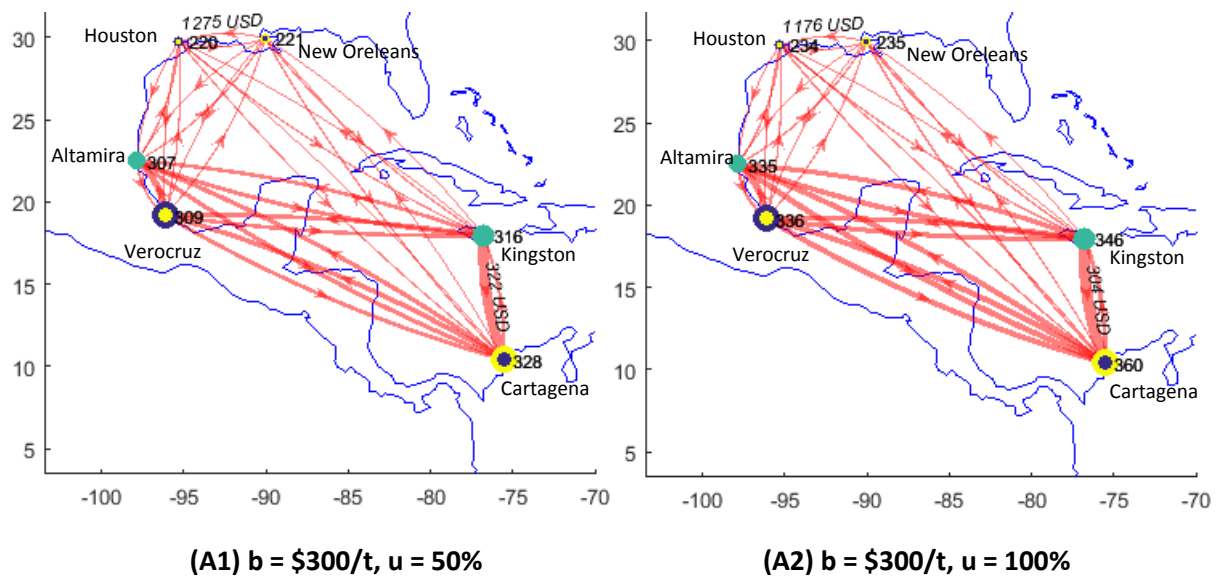
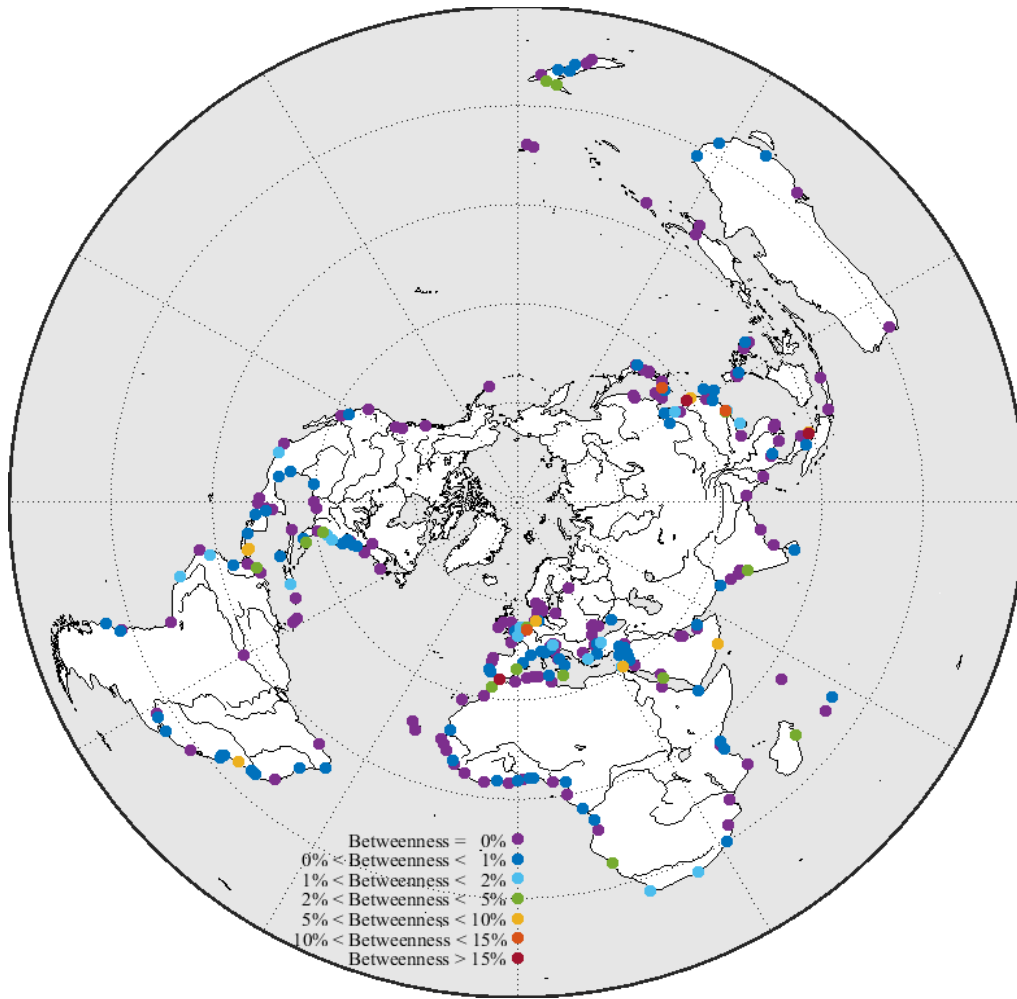


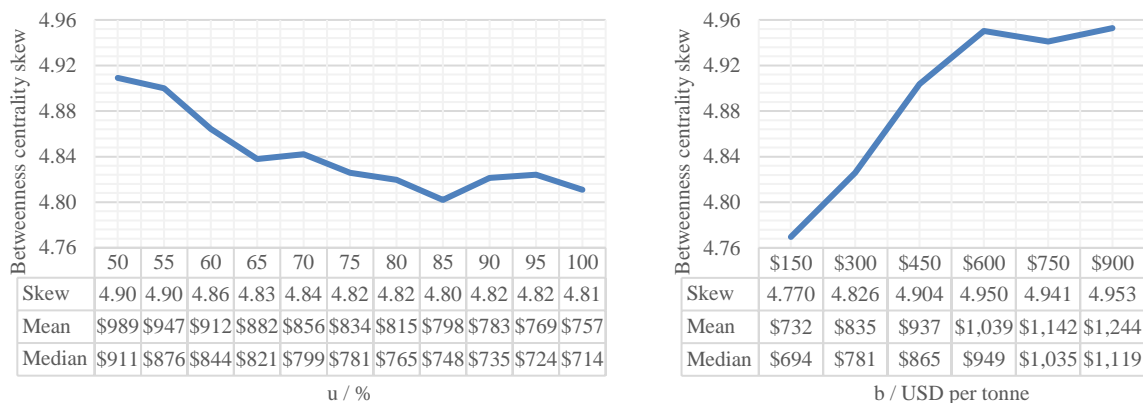
Figure 5: Effect of utilisation on SL Cumbia routes (notation as in Figure 4)

## Global network analyses

We first examine the betweenness centrality (i.e. the number of shortest paths between all pairs of nodes that go through a specific node) of all the nodes. This reveals a highly skewed global network, as shown in Figure 6, with just seven ports acting as a port of transfer for more than 10% of journeys. If one of these ports were compromised by a natural disaster or terrorism, the financial and logistical impact of rerouting vessels and adopting new ports of TEU transfer would be substantial.



**Figure 6: Betweenness centrality, equidistant azimuthal map in MATLAB,  $b = 300$  USD/tonne,  $u = 75\%$**



**Figure 7: Between Centrality skewness against (a) utilisation ( $b = 300$  USD/tonne), (b) bunker fuel price ( $u = 75\%$ )**

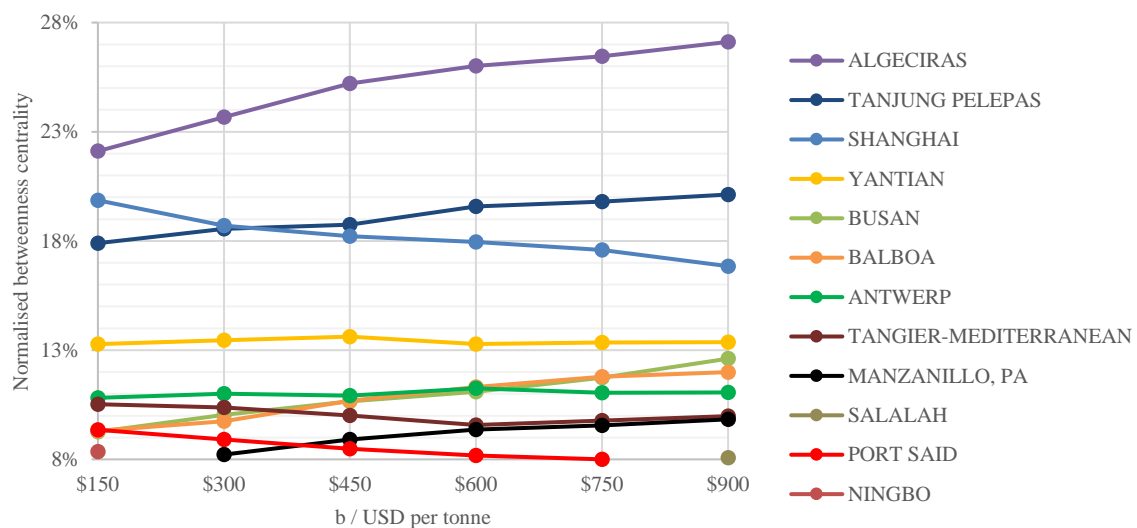
Figure 7 shows the variability of betweenness centrality skewness upon changes to utilisation and bunker fuel prices. The network performs best when the lowest cost journeys between nodes (ports) that are not directly connected (i.e. not on the same route) pass through a wider variety of nodes. In other words, performance is best when the skew in betweenness centrality is low, such that container transfers are



made over a less concentrated selection of ports. This occurs when utilisation is 85%, a value corresponding to the global network utilisation prior to the financial crisis. This suggests that before that time, the network had been optimised to work as smoothly as possible at that utilisation, but insufficient alterations have been made to schedules. The network skewness increases with bunker fuel price, as ports are already clustered around major hubs with greater density than around medium hubs. Therefore, these major hubs prosper as nearby customers are less willing to travel so far to transfer their cargo onto another route.

The response of normalised betweenness centrality, incloseness centrality, and outcloseness centrality to changes in bunker fuel price was then investigated. In addition, the skewness of betweenness centrality values across the global network was taken as a measure of network vulnerability, since it is preferable for the global network to rely on TEU transfers at a multitude of ports rather than a select few.

Figure 8 enables the effects of increasing bunker fuel prices to be explored in more detail. Balboa and Manzanillo, at the Pacific and Atlantic terminuses of the Panama Canal respectively, perform better. However, Tangier-Mediterranean and Port Said, located on the Strait of Gibraltar and the Suez Canal respectively, decrease in prominence. This is largely due to East Asia to US East Coast trade; as fuel prices increase, the cost savings on the shorter eastbound routes relative to the longer westbound routes become more significant.



**Figure 8: Top ten ports by betweenness centrality against bunker fuel price  $b$  (utilisation  $u = 75\%$ )**

Rankings are also introduced for incloseness and outcloseness centralities, as displayed in Figure 9, representing the global import and export hierarchies. In the global import hierarchy, rising bunker fuel prices result in a rapid increase in the prominence of Rotterdam, replacing Antwerp as Northern Europe's most cost-effective destination port. In the global export hierarchy, as bunker fuel prices increase from 300 to 900 USD per tonne, Salalah, Jeddah, and Port Said rise from 2nd, 8th, and 10th to 1st, 2nd, and 8th respectively. Meanwhile, Tanjung Pelepas, Shanghai, and Singapore fall from 3rd, 5th, and 6th to 5th, 7th, and 10th respectively. This is due to East Asia becoming less accessible to the European market due to its geographic distance. It is possible for manufacturing industries based in East Asia to relocate to the Middle East and East Africa, should these countries improve port security and if fuel prices continue to increase. These countries must invest heavily in intermodal connectivity within port hinterlands if they are to benefit from this opportunity. China's transition to a service-based economy as it continues to develop may apply

compound pressures on industries to relocate. Also notable is the closing of the gap between nearby Savannah and Charleston, located in Georgia and South Carolina respectively, despite taking the same handling fees and surcharges and having a two-centimetre draft difference.

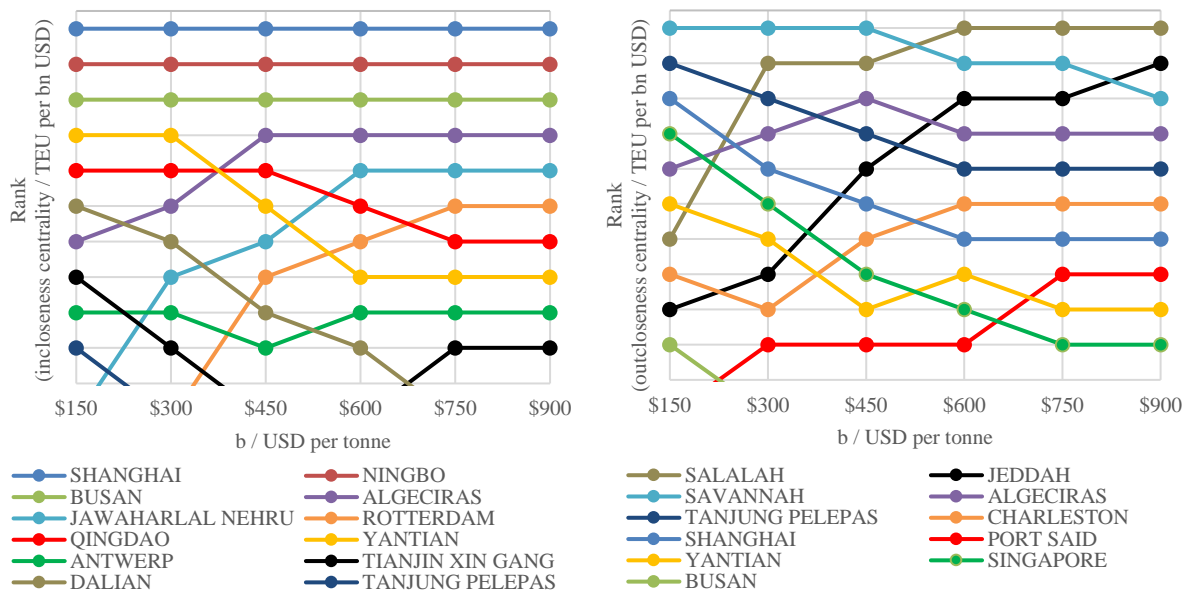


Figure 9: Top 10 ports by incloseness (left) and outcloseness (right) centrality

## Port improvement scenarios

Since canals were found to rarely limit the draft of a route, various port improvement schemes were considered. This was done by clearing the minimum drafts for combinations of ports and rerunning the model. Since a port improvement scheme can take several years, it is assumed that utilisation will climb back to its pre-recession levels of 85% and that bunker fuel prices will rise to 450 USD per tonne by the time the scheme is completed. First, all local routes were examined and a tally of limiting infrastructure was made. All ports with a draft of less than ten metres and limiting at least two scheduled routes were compiled in Table 1.

Table 1: List of ports with a draft less than ten metres by number and routes they limit

Port, p	Route L[p]	Max draft W[p] / m	Port, p	Route L[p]	Max draft W[p] / m	Port, p	Route L[p]	Max draft W[p] / m
Chiwan	18	5.72	Port Elizabeth	4	7.25	Buenos Aires	2	8.27
Ningbo	16	8.25	Tunis	3	6.37	Caucedo	2	8.27
Algeciras	12	8.27	Leghorn	3	6.75	Jeddah	2	8.27
Bremerhaven	10	8.25	Davao	3	7.25	Rotterdam	2	8.27
Ambarli	7	6.37	Sankt-Peterburg	2	5.22	Nelson	2	8.77
Mersin	4	5.22	Porto Di Corsini	2	7.25	Kaohsiung	2	9.80
Durban	4	7.25	Chittagong	2	7.75	Santo Thomas De Castilla	2	9.80

The five ports limiting the greatest number of routes were then combined into all possible combinations of three and four, representing a lower cost and higher cost option, as shown in Table 2. The model was then re-run such that the relevant ports' drafts were ignored. Figure 10 displays the mean and median edge weight, representing the average cost of a direct journey without transfers, alongside the

betweenness centrality skewness. This suggests that scenarios C01 and C03 should be considered further, resulting in the lowest mean cost and the lowest skewness respectively. From comparing scenario C01 with C00 in Figure 10, mean global savings of 60 USD per TEU (median 40 USD per TEU) could be made per direct journey if Chiwan, Ningbo, and Algeciras were to be improved.

**Table 2: Port improvement scenarios**

Case	Port A	Port B	Port C	Case	Port A	Port B	Port C	Port D
C00	No Action, $b = 450 \text{ USD / tonne}$ , $u = 85\%$			C08	Ningbo	Algeciras	Ambarli	-----
C01	Chiwan	Ningbo	Algeciras	C09	Ningbo	Bremerhaven	Ambarli	-----
C02	Chiwan	Ningbo	Bremerhaven	C10	Algeciras	Bremerhaven	Ambarli	-----
C03	Chiwan	Ningbo	Ambarli	C11	Chiwan	Ningbo	Algeciras	Bremerhaven
C04	Chiwan	Algeciras	Bremerhaven	C12	Chiwan	Ningbo	Algeciras	Ambarli
C05	Chiwan	Algeciras	Ambarli	C13	Chiwan	Ningbo	Bremerhaven	Ambarli
C06	Chiwan	Bremerhaven	Ambarli	C14	Chiwan	Algeciras	Bremerhaven	Ambarli
C07	Ningbo	Algeciras	Bremerhaven	C15	Ningbo	Algeciras	Bremerhaven	Ambarli



**Figure 10: Exploration of port improvement scenarios**

## Conclusion

In this paper, a network model of the global shipping routes was created and used to examine its vulnerability to ports becoming unavailable as well as to study the impact of bunker fuel prices and varying utilisation. Several port improvement scenarios were also examined for the gains. The analyses lead to the following conclusions: (a) the network is highly skewed towards few transfer ports, making it vulnerable to high-impact events; (b) routes can be categorised as balanced or imbalanced, affecting their behaviour under price fluctuations; (c) rising bunker prices could divert trade from East Asia from the Suez route to the Panama route; (d) rising bunker prices could harm East Asia's position as an export partner to the European market; (e) mean savings of 60 USD/TEU per journey could be made by improving Chiwan, Ningbo and Algeciras ports.

The findings are based on a network model which covers a large number of routes but not all. It should also be refined to accommodate for backhaul trade imbalance and idle auxiliary consumption, thus allowing the behaviour of imbalanced routes to be studied in more detail. Feasibility studies into port improvement should be made considering market demand and the cost of civil engineering works - this paper considered only the cost savings to be made per journey.